Wildfires in Past Ages

HELENE A. MARTIN

School of Biological Science, University of N.S.W., Sydney 2052

MARTIN, H.A. (1996). Wildfires in past ages. Proc. Linn. Soc. N.S.W. 116, 3–18

Wildfires are a natural part of most ecosystems throughout the world today. Evidence from fossilised charcoal shows that wildfires have occurred in past ages ever since the Devonian. Lightning has been the major source of ignition for wildfires before humans appeared on the planet and it is still responsible for most outbreaks today.

Australian Tertiary examples where the palaeobotanical record indicates a modification of the vegetation associated with fossil charcoal layers is presented here. Even when there was high humidity throughout the year, there would have been dry periods and perhaps droughts when the rainforest dried out sufficiently to burnt, but they were rare. Peat swamps were burnt periodically, but the drier parts burnt more often. After the demise of rainforest in the mid–late Miocene, when *Eucalyptus* became common, burning on a frequent basis became an integral part of the environment. These examples show a close association of vegetation, climate and fire history in a manner compatible with what is seen today.

Manuscript received 1 May 95, accepted for publication 13 Dec 95

KEYWORDS: Tertiary, Fire history, Vegetation history, Fusain, Charcoal, palynology, palaeobotany.

INTRODUCTION

Fire is a natural part of most ecosystems in the world today. Under climates with a well marked dry season, wildfires are regular events and the frequency of firing may be every 3–5 years in the most fire-prone vegetation. In wet climates where the vegetation is too wet to burn, e.g. tropical rainforests, droughts may allow sufficient drying for occasional wildfires. For examples, in mid 1982, an unprecedented drought struck East Java, Sarawak, Sulawesi, Sabah and Kalimantan. A major fire in east Kalimantan burnt between 35,000 and 37,000 square kilometres of tropical rainforest, including the peat-forming areas, where the peat was burnt to a depth of 1–2 m. In these peat swamps, 98–100% of the trees were killed. Records show a drought of almost similar proportions occurred about 90 years earlier (Johnson 1984). Even the tundra may burn. Summer lightning strikes may set fire to the peats which may smoulder, and at times flare up, for months (Komarek 1964). With wildfires a possibility almost everywhere in the world today, were wildfires a part of the ecosystems of past ages?

Microscopic charcoal fragments have long been recognised amongst pollen recovered from swamp sediments. The preserved charcoal has been shown to reasonably reflect fire history constructed from other sources and has led to valuable insights in the dynamics of the vegetation and of human interaction with the environment, where the sediments are only thousands of years old (Singh et al. 1981, Clark 1982, Kershaw 1985, 1986, Patterson et al. 1986).

Macroscopic charcoal is known as fusain of fusinite and may be abundant in lignites and coals, but is also found in other sediments. Although it is generally accepted that fusain is fossilized charcoal, this has not always been the case

The origin of fusain

As early as 1844, it was proposed that lightning fires were the cause of the formation of fusain (Komarek 1972). Physical and chemical evidence gathered from the charcoal burning industry supported this view (Francis 1961). Early in the 1900's, these views were challenged, even though satisfactory alternative hypotheses about the formation of fusain were not proposed. At this time, when the science of forestry was beginning to make a real impact, fire ecology was not understood and the philosophy of the time was that all fires were man-made. As a consequence, all forest fires were regarded as destructive and there were total fire exclusion policies. Komarek (1972) considers it curious, if coincidental, that Germany was the cradle of forestry and the home of some of the world's foremost coal petrologists as well.

In the last decade and a half, there have been a number of studies using modern methods such as scanning electron microscopy and electron spin resonance, to compare fusain, charcoal from forest fires, experimentally burnt and artificially charred plant material. The main results of these studies comparing fusain and charcoal are summarised below.

Physical properties.

Fusain has good three-dimensional structure and fractures along planes into rectangular blocks. It is brittle and is easily pulverised with light pressure. It is fibrous (if the plant material was originally wood), has a low density (unless impregnated with mineral matter), a silky lustre and high reflectance (Jones et al. 1991). These properties are very similar to those of charcoal and fusain has the general appearance of charcoal (Harris 1958, Francis 1961, Cope and Chaloner 1980, Scott 1989).

Chemical properties.

Analysis of fusain shows 77–94% carbon and 2–3% hydrogen, an analysis also typical of charcoal (Francis 1961, Scott 1989). Both fusain and charcoal are inert and resistant to maceration (Harris 1958, Sander and Gee 1990). Fusain has low flammability and does not catch alight, it merely glows, as does charcoal. Fusain is unaffected by pyrolysis and electron spin resonance studies suggest that the origin of fusain involve exposure of wood to temperatures of 400–600°C (Austen et al. 1966, Teichmüller 1982). These temperatures are commonly encountered in wildfire (see Scott 1989). In natural fires, temperatures vary enormously (Whittaker 1961, Kenworthy 1963), producing anything from partially charred plant material which remains biodegradable to completely charred material, and if temperatures are extreme, complete combustion may reduce it to ash (Harris 1981, Scott 1989).

Being mainly inert carbon, charcoal is not biodegradable, hence preservation is usually excellent. It has long been known that the charring of wood aids in its preservation. The early pioneers of the U.S.A. superficially charred the fence posts before placing them in the ground (Komarek 1972).

Microscopic examination

Both fusain and charcoal may show excellent cell detail and even delicate structures such as pits are well preserved. The cells retain their three dimensional character and are not deformed, but they may be crushed, whereas cellular tissue preserved by other means (e.g., in swamps and bogs) shows characteristic deformations with pressure. The cell wall has been homogenised and no structures are visible, whereas cells preserved by other methods may show the middle lamella (McGinnes et al. 1974, Cope and Chaloner 1980, Prior and Alvin 1983, Scott 1989, Sander and Gee, 1990). Experiments show that the microfibrillar structure of wood subjected to temperatures up to 240°C is not visibly altered (Beck et al. 1982) but charring in a commercial charcoal kiln where maximum temperatures reached are 280–400°C, the original fibrillar arrangement of the wall is replaced with an amorphous-appearing wall structure (McGinnes et al. 1971).

Most fusain originates from wood, but leaves and flowers showing excellent cell detail have been found also (Alvin 1974, Friis et al., 1982, Scott 1989). Experiments (Harris 1981) in which dry *Pteridium* fronds were set alight, produced burnt fragments retaining their delicate cell structure, and these fragments are similar to carbonized fossil leaves of ferns showing cell detail of the palisade and spongy mesophyll. Even stomates and the hairs on the surface of the leaf may be found in burnt litter after a wildfire Other dry leaves may be more delicate and burn completely to ash in experiments, but they may retain their cell structure if on the forest floor, where temperatures are lower during a forest fire (Harris 1958, 1981). Delicate leafy liverworts have been observed to be carbonized and preserved in brown coals (Blackburn and Sluiter 1994). Charring by a peat fire, some 50 cm below the surface, produced excellent preservation of roots (Teichmüller 1989).

Modification of the vegetation

Changes in the vegetation following modern fires are well known, and modifications in the spore–pollen composition associated with layers of fusain in Tertiary peat environments have been reported. Grebe (1953) examined the pollen floras associated with layers of fusain in some German brown coals. In one layer, the fusain had been transported in by water. In another layer, where the habitat was quite damp, it was only lightly burnt and the forest was not changed by the fire. The interpretation of yet another layer is that the peat had burnt and afterwards, the pollen of a number of ferns and insect pollinated plants, usually rare in these coals, had become common. The fire and the changes in the coal vegetation are comparable to those seen on moors today (Grebe 1953). Such changes have been observed following wildfires in the Okefenokee swamp of the eastern coastal plain of the U.S.A., after a severe drought. When the peat burns, it destroys the root systems of the trees and lakes or 'prairies' are formed. The peat fires are localized and spotty. Eventually, the swamp forest returns (Cypert 1972).

Alternative hypotheses

The evidence for wildfires being the origin of fusain would seem convincing, but there are alternative hypotheses still accepted by some. Aerobic bacterial attack or oxidation of plant material at the surface of a swamp may be proffered, but the high content of volatile matter in material subjected to these processes distinguishes it from fusain. Moreover, bacterial attack would degrade the fine cellular structure and could not produce the excellent preservation of fusain. Wood suffering attack by dry rot fungi shrinks and cracks like charcoal, but the cell walls are grossly degraded, unlike those of fusain (Harris 1952). There are other hypotheses (see Scott 1989), but they seem to result from a disbelief that there could have been wildfires in the past. For example, 'The charcoal theory of origin of fusain is principally objectionable because it is commonly taken to be an indication of periodic drought and a susceptibility of vegetation to conflagration for which all other evidence is lacking ... For some and probably the majority of the occurrences of fusain, the forest fire seems ruled out. It is unfortunate that I am not able to suggest any generally applicable alternative hypotheses' (Schopf 1975, p 45). There may be so much fusain that if produced by wildfire, the past would have been a 'fiery nightmare'. Over-representation, when unburnt material has decayed (Harris 1952), or the peat has burnt (Scott 1989), leaving only the fusain, may account for these quantities. For a detailed review of this old controversy, see Scott (1989).

The principal objectors to the theory that fusain is fossilised charcoal come thus from those who are unfamiliar with the behaviour of forest fires and who cannot believe that wildfires may burn out swamps or forests in very wet climates, and that periodic droughts occur, even in the wettest of climates. There is, however, ample evidence to show that this disbelief is mistaken. During an extreme drought in 1954 and 1955, fires swept over the Okefenokee Swamp, burning out approximately 128,700 hectares of swamp and 56,660 hectares of upland (Cypert 1972). Many such swamps are known as fire environments (Komarek 1972) and 'most Holocene peats are subject to destruction by erosion, fire and ...' (Cameron et al. 1989, p 105). The fauna of marshes and swamps may rely on regular burning to keep the habitat open and maintain their food supplies. Some of these environments in the eastern coastal plain of the U.S.A. are managed with planned burning, for they are important feeding grounds for migrating birds (Komarek 1974).

Studies of surface sediments and cores from the Florida Everglades traced the development of peat from plant material in an attempt to explain the origin of the coal fractions (Cohen and Spackman 1977). In these studies, the highest content of fusain is found in the driest of the swamp environment. 'No evidence is found to support the hypothesis that fusinite in coal can be derived from any process other than fire' (Cohen and Spackman 1977, p.72). In these environments, fires spread through the vegetation above water and the stems below water remain unburnt (Teichmüller 1982). There is no evidence to support alternative hypotheses of the formation of fusain

Charcoal in the geological record

Charcoalified plant material may be locally abundant in many post-Devonian sediments (Cope and Chaloner 1980). It is not restricted to coal, but may be abundant in silts and clays. Charcoal, being light, would be easily transported by water or air currents, particularly at the time of the fire. The evidence from fusain in Lower Carboniferous rocks of Ireland indicates a 'catastrophic palaeowildfire' (Nichols and Jones 1992, p 487). The volume of fusain is compared with the charcoal production from modern fires and it has been calculated that around 95,000 square kilometres were burnt. This fire resulted in increased runoff and increased sediment deposition in the tidal environment, probably an estuary (Nichols and Jones 1992). Scott (1989, p 445) concludes 'that wildfires have been a feature of terrestrial ecosystems from at least the Late Devonian'. Jones and Chaloner (1991) review wildfires through geological time and conclude that spontaneous wildfires are, perhaps, an essential element in the evolution of the ecosystem.

The source of ignition

The main source of ignition for these wildfires would have been lightning strikes (Scott 1989). Even today, up to 80% of fires in western Queensland are started by lightning and 'lightning causes more fires in Australia than is generally realised' (Luke and McArthur 1978, p.61). In North America, frontal weather systems in summer sweep down the eastern side of the Rockies at about 7–14 day intervals, bringing with them thunderstorms and lightning and setting fires as they travel southeastwards (Komarek 1972). Lightning is of such frequency and magnitude that most ecosystems are subjected to recurring lightning fires. For a fascination account of 'The Natural History of Lightning', see Komarek (1964).

Under certain circumstances, lightning striking an exposed sandy surface may fuse the grains into glassy, dendritic shapes called fulgurites. There may be woody fragments in a central hollow tube, suggesting that the lightning travelled down a stem or root. Fulgurites are common in Quaternary sands near Perth (Kemp 1981), but they may be of any age. Harland and Hacker (1966) report fulgurites from the Palaeozoic. Komarek (1964) records a lightning fire in a Florida forest, but the ranger was unable to find the struck tree. About a week later, a wilting cabbage palm tree (*Sabal palmetto*) was noted. When cut down it was found that the lightning had apparently gone down the inside of the tree, then through the sandy soil a metre or so, apparently igniting a clump of palmetto bushes which contained much flammable material. Where the discharge had gone through the sand, it had fused some of the grains into fulgurites (Komarek 1964).

Where coal seams outcrop, they may ignite spontaneously, thus being a source of ignition for wildfires (Kemp 1981). In New South Wales, a burning coal seam at Wingen has been known from earliest European settlement (Rattigan 1967) and the same seam is still burning at Burning Mountain. Intense localised heat from coal seam fires may fuse the sedimentary rock, and such evidence has been found in the Bowen Basin of Queensland, Leigh Creek of South Australia and other locations in the Sydney Basin, as well as Wingen. For a full review of geological evidence of fire, see Kemp (1981).

In the thick brown coals of the Latrobe Valley, Victoria, there are a number of fire holes. These depressions in the coal have carbonised coal, similar to charcoal at the base and are filled with clay. In some holes, the clay has been baked into a brick-like material due to the fire continuing to burn after the deposition of the clays (Gloe 1960).

Glowing ash and lava fragments from volcanic activity are another potential source of ignition. Volcanoes were active in the southeastern highlands during the Tertiary and more recently in the southwest of Victoria and southeast of South Australia. There is a report of carbonized tree trunks in the Triassic Brisbane Tuffs (Kemp 1981).

The impact of meteorites may be another source of ignition, although rare. Studies of the Cretaceous–Tertiary boundary clays in Europe and New Zealand (Wolbach et al. 1988) show an enrichment in elemental carbon, mainly soot. (Soot forms in the higher temperatures found in flames whereas charcoal is formed by charring at lower temperatures). This enrichment of carbon is associated with the iridium layer (Wolbach et al. 1988), which is thought to be of extraterrestrial origin (Alvarez et al. 1988). The soot is isotopically uniform, suggesting that it comes from a single global fire. Most likely, major wildfires were triggered when trees were killed and dried by the impact, both by the prompt heating of the atmosphere and by strong winds capable of flattening forests out to a distance of 500–1,000 km, and subsequent heating by the ejecta plume and hot fallout (similar to volcanic ash). The soot from these fires settled together with the iridium (Wolbach et al. 1988).

CHANGES IN THE VEGETATION ASSOCIATED WITH CHARCOAL LAYERS

Australian examples of changes in the Tertiary vegetation associated with charcoal layers are discussed here

The Latrobe Valley Brown Coals

The Latrobe Valley Depression, in the western part of the onshore Gippsland Basin (Fig. 1), contains some of the thickest and most continuous deposits of brown coal in the world (Gloe 1960). The extensive coal swamps were vegetated raised bogs (Blackburn 1981) with lakes around much of their margins, thus isolating them from sediment input (Holdgate 1985). The swamps were essentially rain-fed and would have been poor in nutrients, most of the nutrients coming from recycling. The deposits are mid Eocene to mid Miocene in age.

Because of their economic importance, there have been numerous studies of the geology, assessment of the coal and the palaeobotany, both macro- and microfossils (see the review by Blackburn and Sluiter 1994). This paper concentrates on the palaeobotanical studies which show changes in the vegetation associated with charcoal layers.

Earlier workers on the Latrobe Valley brown coals (e.g. Edwards 1953, Baragwanath 1962) rejected the notion that fusain originated from fire, in keeping with the general opinion of the time. Recent workers, however, accept that the fusain is indeed fossil charcoal (Teichmüller 1982, Blackburn 1981)

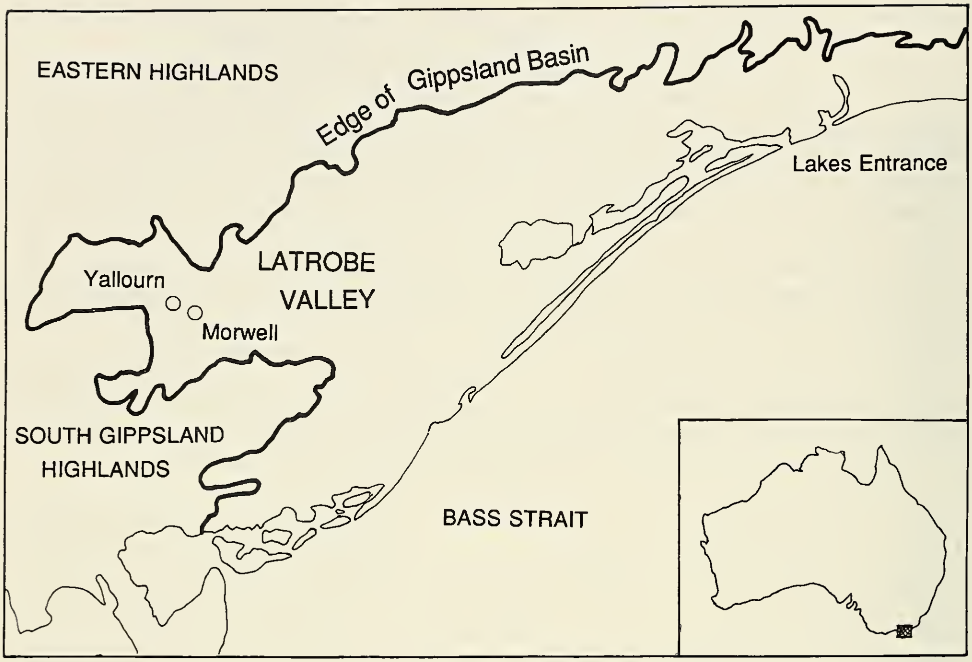

Fig. 1. Locality map of the Latrobe Valley brown coals.

The brown coal resembles peat and macroscopic remains of plants are clearly visible (Teichmüller 1989). The coal varies in colour from light or pale to very dark and a number of lithotypes have been defined using colour. Very dark, dark, medium dark and medium light lithotypes were formed from swamp forests, with the peat surface being generally (dark) or seasonally (medium light) emergent. The very dark coals have a high charcoal content and are indicative of the driest environments. The light to pale lithotypes were probably formed under inundated conditions (Blackburn and Sluiter 1994). The coal usually shows light and dark banding (Blackburn 1981).

The Yallourn seam coals are latest early Miocene to mid Miocene. The basal coals have a high fusain content (35–60%). The vegetation had abundant monocotyledons (Typhaceae, Sparganiaceae, Restionaceae) and Proteaceae (*Banksia, Xylomelum* and others). The Myrtaceae in these coals are those of modern swamp heaths (*Baeckea, Leptospermum, Melaleuca*). Carbonised leafy liverworts are common. Gleicheniaceae is also common in coals with a high fusain content. These reedy swamps with ferns and sclerophyllous shrubs dried out seasonally and the community was largely controlled by fire (Blackburn and Sluiter 1994).

The medium dark to light coals are dominated by Podocarpaceae (*Dacrydium* and *Dacrycarpus*, with *Phyllocladus* locally common), Araucariaceae (*Agathis* and locally *Araucaria*) and Oleaceae. Myrtaceae are also widely distributed and may be assigned to *Syzygium, Tristania* and *Acmena* (Blackburn and Sluiter 1994). The relationships between the vegetation with water levels and the influence of fire is illustrated in Fig. 2.

An erosional layer 5 cm thick, containing abundant charcoal, identifiable over an area of approximately 8 square km, is found in the Morwell Coal Seam. This layer is late Oligocene in age. A section 1.3 m in thickness was sampled at 5 cm intervals across this layer, approximately 60 cm below and 70 cm above it. The darkest coal colour occurs at the

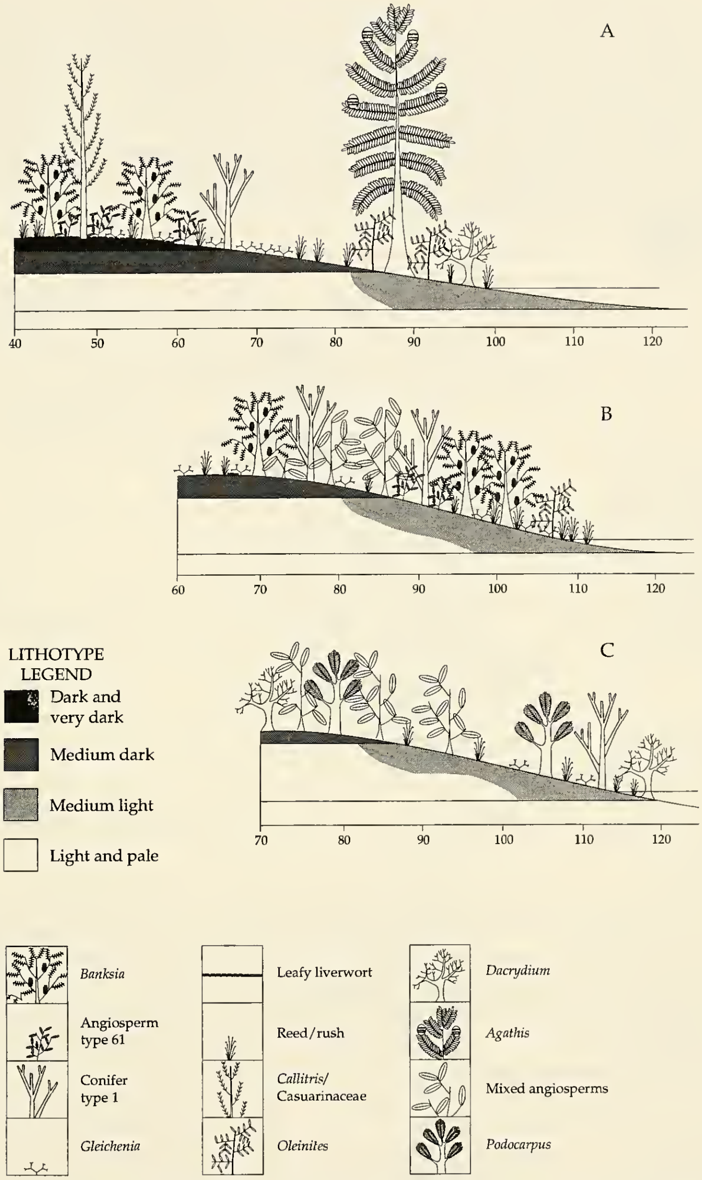

Fig. 2. Hydroseral and pyric succession for three intervals from Yallourn open cut. A to C are arranged in order of decreasing fire influence. Water levels indicate probable permanent inundation. A. Succession under the influence of frequent fires. The margins of open water are essentially a *Dacrydium–Oleinites–Agathis*-reed/rush swamp. On drier areas above this is a reed/rush–*Gleichenia* moor. This grades into a *Banksia–Gleichenia*-conifer type 1-reed/rush scrub. Rare *Callitris* and Casuarinaceae occur on the driest parts with leafy liverworts. B. Succession under the influence of infrequent fires. The margins of open water are occupied by an *Oleinites–Gleichenia*-reed/rush swamp. On drier areas above this is a *Banksia–Gleichenia*–angiosperm type 61-conifer type 1 scrub. Above this again is a region having a mixed angiosperm scrub. On the driest parts *Banksia–Gleichenia*-reed/rush scrub dominates. C. Succession under the influence of very infrequent fires. The margins of the open water are colonised by *Dacrydium–Gleichenia*–conifer type 1-reed/rush swamp. On the drier areas there is a mixed angiosperm–*Podocarpus–Dacrydium* scrub. Reprinted from Blackburn and Sluiter (1994), with permission of Cambridge University Press.

base of the charcoal layer and the colour becomes progressively lighter above it, terminating in light colour at the top. The macrofossils present would have been growing close to the site of deposition, but the microfossils (spores and pollen) could have come from afar.

Major changes in the contributions of the dominant macro- and microfossil plant groups are observed, particularly in the vicinity of the charcoal layer. Some taxa tend to be most abundant below the layer whereas others are more common above it. There is a group which does not change much, above and below the layer. (Blackburn and Sluiter 1994). These major changes are summarized in Table 1.

TABLE 1

Summary of the major changes in dominants from before to after a 'big burn' in the Morwell Coal Seam, age late Oligocene. From Blackburn and Sluiter (1994).

REGIONAL VEGETATION	
Dominant — *Nothofagus* — not growing in swamp (pollen blown in on the wind)	
Swamp Vegetation	
Dominant Taxa	
1. After the fire	
Casuarinaceae	*Allocasuarina* Gymnostoma
Cunoniaceae	'*Phyllites*' and others
Myrtaceae	*Tristania* (most) *Acmena* *Baeckia/Leptospermum* *Syzygium, Austromyrtus*
Gleicheniaceae	*Gleichenia*
Typhaceae / Sparganiaceae	
Erosional Layer 'Big Burn' with Charcoal	
2. Before the fire	
Proteaceae	*Banksia* *Xylomelum* and other taxa
Podocarpaceae	*Dacrydium* *Dacrycarpus*
Araucariaceae	*Araucaria/Agathis*
Cunoniaceae	*Ceratopetalum*
Saxifragaceae	*Quintinia*
Liliaceae/Restionaceae	

Murray Basin

The Murray Basin (Fig. 3) was a giant flood plains complex, fed by the major rivers draining the Eastern Highlands. From time to time, the rivers would change course, dumping the sediment load elsewhere and former swamps would develop soil horizons. There was thus a shifting pattern of swamps and dry land. The pollen bearing deposits are late Eocene to mid Miocene in age. Unfortunately, the top 50–100 m of sediment rarely contain pollen (Martin 1984a, 1984b, Brown 1989, Macphail and Truswell 1989). The pollen from about 100 bores in the Basin have been studied (Martin 1993).

From late Eocene to mid Miocene, the vegetation was predominantly rainforest and *Nothofagus* spp. were common. *Podocarpus* was usually the most common gymnosperm, with *Dacrydium* and *Dacrycarpus* usually present. *Lagarostrobos* and Araucariaceae were

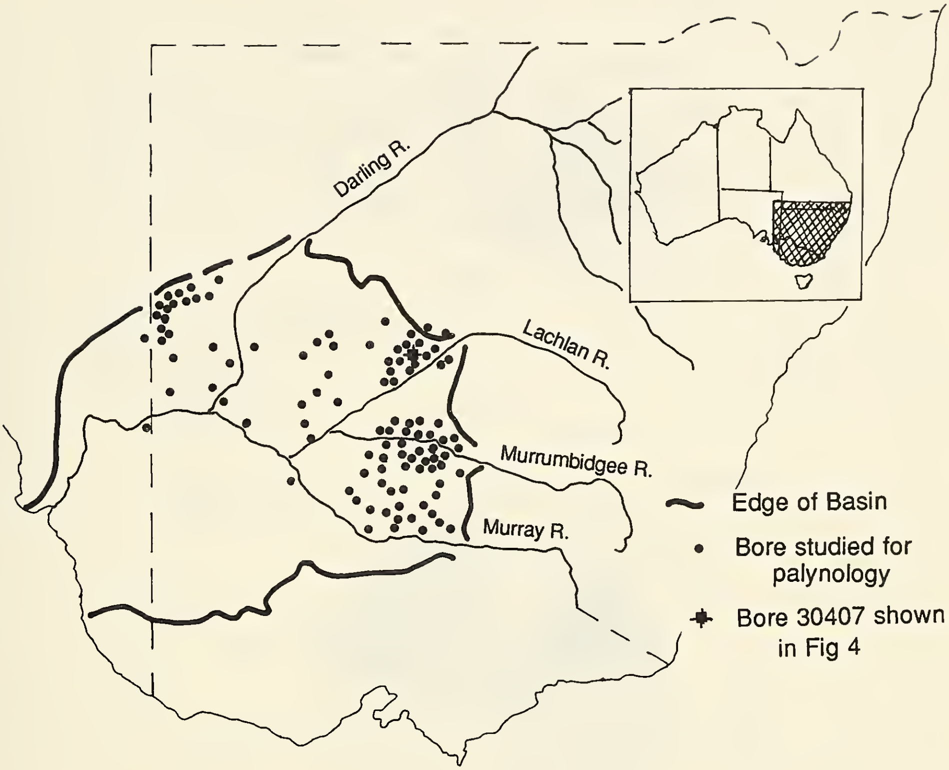

Fig. 3. Locality map of the Murray Basin.

sometimes abundant. Myrtaceae (mostly pollen of rainforest taxa with few of eucalypts) were usually present and Casuarinaceae, generally in low frequencies, was sometimes abundant. Herbaceous or low growing taxa, e.g. Restionaceae, Cyperaceae, Sparganiaceae and rarely Poaceae and Asteraceae were present in low frequencies. There was a wealth of other angiosperm taxa which, being under represented in the pollen fall-out, were only recorded in low frequencies (see Martin 1993).

The climate was very wet and the precipitation would have been above 1500 mm, with relatively high humidities throughout the year (Martin 1987). Such a climate would not be conducive to wildfires.

There is a low frequency of small carbonised particles in most of the sediments (discussed further, below). Charcoal is relatively inert, and may be reworked, with larger pieces being broken into smaller pieces, thus maintaining a low background count. Higher counts are extremely rare in the Murray Basin. In one bore, however, (Fig. 4) one sample shows unusually high Casuarinaceae and exceptionally low *Nothofagus* counts. The counts for fern spores and herbs are high also. This anomalous sample has an unusually high content of carbonized particles. The samples above and below it, both with abundant *Nothofagus*, are more or less average for this time. The *Nothofagus* rainforest had been replaced by more open forest with Casuarinaceae dominant after a fire, which after time, reverted to the usual *Nothofagus* forests (Fig. 4). Even though the climate was very wet, there would have been dry spells and droughts when the vegetation may have dried out sufficiently to burn, but such events were extremely rare (Martin 1993).

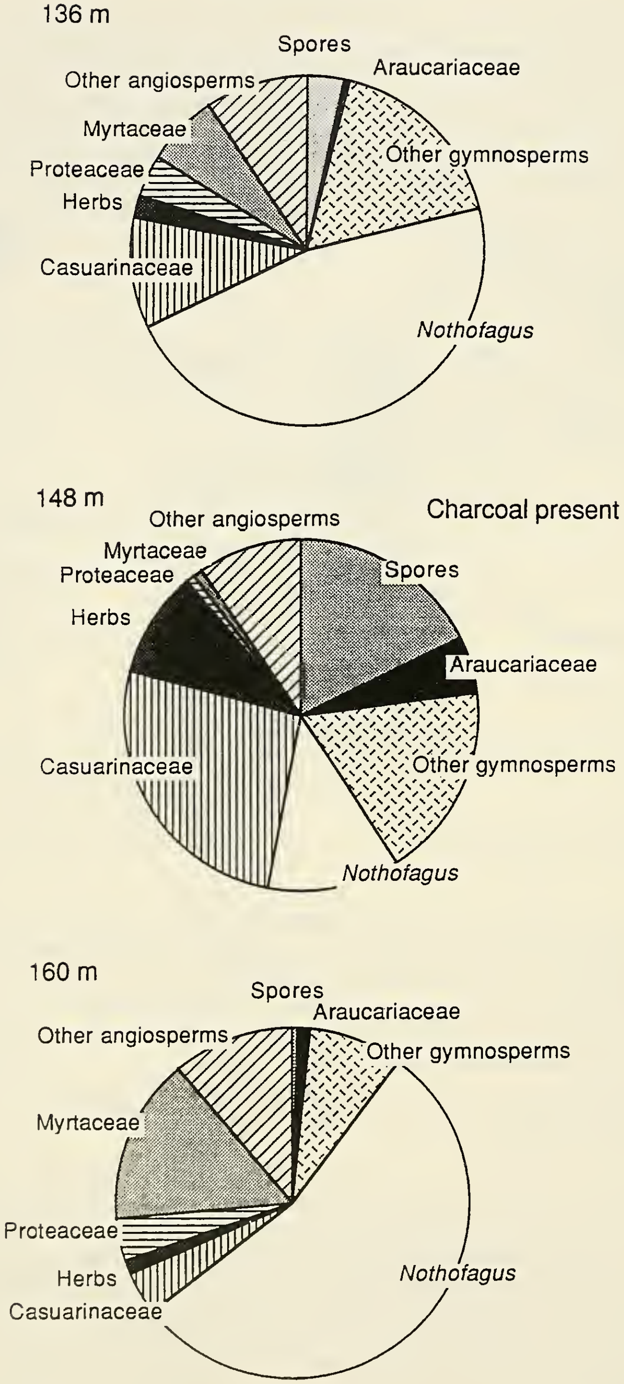

Fig. 4. A sequence of three consecutive samples from bore 30407 (see Fig. 3 for locality). The spectra from 136 m and 160 m are more or less 'average' and that from 148 m is most likely a modification after burning, from Martin (1993).

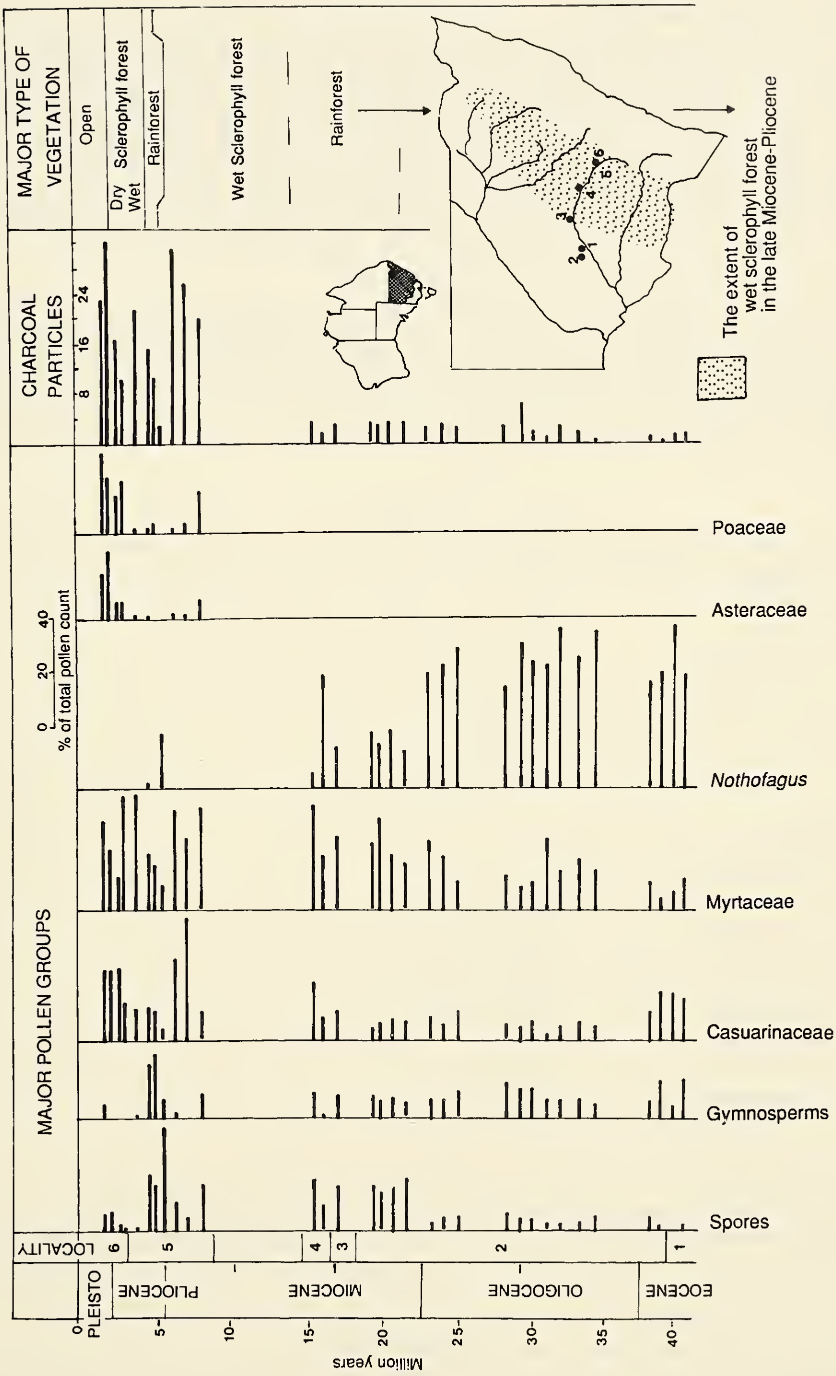

Fig. 5. The major pollen groups, carbonised particle counts (expressed as the ratio carbonised particles/total spores and pollen) and type of vegetation of the Lachlan River Valley. The sequence is a composite of bores, with the locations shown on the inset map (Martin 1978). For further explanation, see text..

The Lachlan River Valley

A series of bores along the Lachlan River presents an almost continuous record from the late Eocene to late Pliocene–Pleistocene. Fig. 5 shows counts of the major pollen groups, and carbonized particles together with interpretations of the palaeovegetation.

From late Eocene to mid Miocene, the major type of vegetation was rainforest. *Nothofagus* was usually common and the Myrtaceae group included mainly rainforest taxa. The pollen assemblages for this time period shown here in Fig. 5 are very similar to the upper and lower levels of the bore represented in Fig. 4, but this latter bore has not been used in this section along the Lachlan River Valley. The charcoal or carbonized particle count is the low background count throughout.

In the mid–late Miocene, there was a drastic change. *Nothofagus* and many other rainforest taxa disappear or are drastically reduced. Myrtaceae has become the dominant group and although much of the Myrtaceae pollen is difficult to identify, the eucalypt type is fairly common. This change is accompanied by a dramatic increase in charcoal particles, suggesting that fire had become an integral part of the environment, and that eucalypts were common in the vegetation (Martin 1987).

TABLE 2

Rainforest taxa in the late Miocene–Pliocene of the Lachlan River Valley, from Martin (1978).

	Family	Taxon
Gymnosperms		
	Araucariaceae	Araucariaceae
	Cupressaceae	Cupressaceae
	Podocarpaceae	*Podocarpus*
		Dacrydium
		Dacrycarpus
		Phyllocladus
Angiosperms		
	Aquifoliaceae	*Ilex* (rare)
	Elaeocarpaceae	Elaeocarpaceae
	Euphorbiaceae	*Coelybogyne*
		Macaranga–Mallotus
	Proteaceae	*Helicia–Orites*
	Rubiaceae	*Gardenia*
	Sapindaceae	Cupaneae
	Saxifragaceae	*Quintinia*
	Symplocaceae	*Symplocos*
	Winteraceae	*Tasmannia*

The late Miocene–Pliocene palaeovegetation with abundant Myrtaceae (mostly eucalypts), with some rainforest taxa (see Table 2) and in which burning would have occurred on a regular basis, best fits wet sclerophyll forest which has a tall open canopy of *Eucalyptus*, rainforest taxa in the understorey or as a small tree layer and in which 'fire is an integral part of the environment' (Ashton and Atiwill 1994). Tree ferns (*Cyathea*) may be abundant in wet sclerophyll forest, and spores of *Cyathea* are common amongst the pollen counts. This palaeovegetation is unlikely to have been rainforest, for rainforest rarely burns (Webb 1970, Luke and McArther 1978). If wet sclerophyll forest remains unburnt, it will revert to rainforest, but if the climate has a marked dry season conducive to wildfires on a regular basis, then this reversion is unlikely.

There is one level in the early Pliocene (see Fig. 5) where *Nothofagus* and some other rainforest taxa make a brief comeback. At this level, the carbonized particle count is much reduced and is similar to that of the older part of the sequence when rainforest flourished (Martin 1987). This level marks a short-lived increase in rainfall which would have reduced the fire frequency and allowed rainforest to increase.

The Lachlan River Valley has the best sequence and is shown in Fig. 5, but the other major river valleys down the Western Slopes have very similar sequences (Martin 1991). The likely extent of wet sclerophyll forest in the late Miocene–Pliocene is shown on Fig. 5 also.

DISCUSSION

In view of the experimentation and the number of studies comparing fusain to charcoal, there seems little doubt that fusain is fossilised charcoal and it may be recovered from sediments in considerable quantity. Wildfires may burn in practically every kind of vegetation today, even that growing in very wet climates during times of drought, hence it is not unreasonable to expect wildfires in past ages. The prerequisites for wildfires are: 1, fuel, the vegetation: 2, the fuel must dry out sufficiently to burn, i.e., a climatic prerequisite and 3, there must be a source of ignition, usually lightning before the arrival of man. It is not difficult to realise these three conditions.

Modifications of vegetation following fire are well known today, and the palaeobotany indicates modifications in the vegetation associated with fossil charcoal layers. There are several Australian examples of such modifications of mid–late Tertiary age, when the climate was wetter than that of today.

Examples from the Latrobe Valley and Murray Basin are late Oligocene–mid Miocene in age, and the dominant type of vegetation was rainforest with common *Nothofagus*. The example from the Murray Basin records modifications in the vegetation associated with a charcoal layer. The *Nothofagus* rainforest was replaced by a more open forest with Casuarinaceae dominant, which in turn reverted to *Nothofagus* rainforest. The coal swamp vegetation in the Latrobe Valley did not contain *Nothofagus* which, however was present in the surrounding regional vegetation. Sclerophyllous taxa, e.g., *Banksia* and other Proteaceae were common and sometimes abundant in these swamps, not because of xeric conditions but because of the low nutrient status (Blackburn and Sluiter 1994). Changes in the composition of the vegetation associated with charcoal are complex, but they usually include increased Casuarinaceae. It is interesting to note that although *Eucalyptus* had evolved by this time (Martin 1994), it was not common and not involved with fire ecology in these examples from the Tertiary rainforests. *Eucalyptus* of the late Oligocene–mid Miocene thus responded in a very different manner to that of today when it replaces rainforest after burning.

The mid–late Miocene of the Lachlan River Valley registers the demise of rainforest as the major type of vegetation and the establishment of burning as an integral part of the environment. The charcoal particle frequencies are closely correlated with the spore–pollen frequencies. *Eucalyptus* and Casuarinaceae were dominant in the vegetation. No doubt, these levels of *Eucalyptus* were maintained by burning which was part of the late Miocene and Pliocene environment. There is a minor resurgence of rainforest in the early Pliocene and the charcoal particle frequency drops to the level of that associated with the Oligocene–mid Miocene rainforest.

CONCLUSIONS

Numerous studies on apparent fossilized charcoal show that it has all the properties of charcoal and it has been formed from burning of plant material.

Fossilized charcoal, may be found in sediments of post-Devonian age and is evidence that wildfires were part of the environment of past ages.

Increased concentrations of charcoal may be accompanied with modifications in the vegetation compatible with what is seen today.

In the Oligo–Miocene *Nothofagus* rainforests, wildfires were extremely rare. One instance of an increase in charcoal concentration was accompanied with a change to Casuarinaceae dominated, more open vegetation, which, after a time, reverted to *Nothofagus* forests.

In Oligo–Miocene nutrient-poor sclerophyllous swamp vegetation, an increase in charcoal concentration is also accompanied by a change to more Casuarinaceae in the vegetation.

In the late Miocene–Pliocene, when widespread rainforest had been mostly replaces by *Eucalyptus* forests, there is a consistently higher level of charcoal particles when compared with the former rainforests.

These associations of fire history and modifications in the vegetation, when considered together with the climate of the time, are entirely compatible with what is observed today.

ACKNOWLEDGEMENTS

Discussions and criticisms from colleagues are appreciated. Material from New South Wales was supplied from the Department of Water Resources.

REFERENCES

Alvarez, L.W. Alvarez. W., Asaro. F. and Michel, H.V. (1980). Extraterrestrial cause for the Cretaceous Tertiary extinction. *Science* **208,** 1095–1108.

Alvin. K.L. (1974). Leaf anatomy of *Weichselia* based on fusainized material. *Palaeontology* **17,** 587–598.

Ashton, D.H. and Atiwill, M.P. (1994). Tall open-forests. In 'Australian Vegetation' Second Edition (Ed. R.H.Groves) pp 121–151. (Cambridge University Press, Cambridge).

Austen, D.E.G., Ingram, D.J.B., Given, P.H., Binder, C.R. and Hill, L.W., (1966). Electron spin resonance study of pure macerals. In: R.F. Gould (Editor), Coal Science. *American. Chemical Society, Advances in Chemistry Series* **55,** 344–362.

Baragwanath, G.E. (1962). Some aspects of the formation and nature of brown coal, and the behaviour of brown coal ash in water tube boilers with special reference to Victorian deposits. *Proceedings, Australian Institute of Mining and Mineralogy* **202,** 131–249.

Beck, C.B., Coy, K. and Schmid. R., (1982). Observations on the fine structure of *Callixylon* wood. *American Journal of Botany* **69,** 54–76.

Blackburn, D.T., 1981. Plant fossils of the Latrobe Valley. International Botanical.Congress Field Trip 37. (Unpubl.) 13 pp.

Blackburn, D.T. and Sluiter, I.R. 1(994). The Oligo–Miocene coal floras of southeastern Australia. In . "History of the Australian vegetation: Cretaceous to Recent' (Ed. R.S. Hill) pp. 328–367. (Cambridge University Press, Cambridge).

Brown, C.M. (1989). Structural and stratigraphic framework of groundwater occurrence and surface discharge in the Murray Basin, southeastern Australia. *B.M.R. Journal of Australian Geology and Geophysics* **11,** 127–146.

Cameron. C.C.. Esterle, J.S. and Palmer, C.A. (1989). The geology, botany, and chemistry of selected peat-forming environments from temperate and tropical latitudes. In 'Peat and Coal: Origin, Facies, and Depositional Models'. (Eds P.C. Lyons and B. Alpern). *International Journal of Coal. Geology* **12,** 105–156

Clark, R.J. (1982). Point count estimation of charcoal in pollen preparations and thin sections of sediments. *Pollen et Spores* **24,** 523–535.

Cope. M.J. and Chaloner, W.G. (1980). Fossil charcoal as evidence of past atmospheric composition. *Nature (London)* **283,** 647–649.

Cohen, A.D. and Spackman, W. (1977). Phytogenic organic sediments and sedimentary environments in the Everglades–mangrove complex. *Palaeontographica Abt. B* **162,** 1–144.

Cypert, E. (1972). Plant succession on burned areas in Okefenokee swamp following the fires of 1954 and 1955. *Proceedings of the Tall Timbers Fire Ecology Conference* **12,** 199–217.

Edwards, A.B. 1953 Fusain in some Victorian brown coals. *Proceedings of the Australasian Institute of Mining Metallurgy* **170,** 47–66.

Francis, W. (1961). 'Coal' Second Edition. (Edward Arnold, London)

Friis, E.M. and Skarby, A. (1981). Structurally preserved angiosperm flowers from the Upper Cretaceous of southern Sweden. *Nature (London)* **291,** 485–486.

Gloe, C.S. (1960). The geology of the Latrobe coalfield. *Proceedings of the Australasian Institute of Mining Metallurgy* **194,** 57–125.

Grebe, H. (1953). Beziehungen zwischen Fusitlagen und Pollenführung in der Rheinischen Braunkohle. *Palaeontology* **27,** 12–15.

Harris, T.M. (1958). Forest fire in the Mesozoic. *Journal of Ecology* **46,** 447–453.

Harris, T.M. (1981). Burnt ferns from the English Wealden. *Proceedings of the Geologists Association, London* **92,** 47–58.

Harland, W.B. and Hacker, J.L. (1966). 'Fossil' lightning strikes 250 million years ago. *Advances in Science* **22,** 663–671.

Holdgate, G.R. (1985). Latrobe Valley brown coals, their geometry and facies equivalents as a guide to depositional environment. *Australian Coal Geology* **5,** 53–68.

Johnson, B., 1984. The Great Fire of Borneo. (World Wild Life Fund, Godalming, Surrey, U.K.) 24 pp.

Jones, T.P. and Chaloner, W.G. (1991). Les Feux du passé. *La Recherche* **22,** 1148–1156.

Jones, T.P., Scott, A.C. and Cope, M. (1991). Reflectance measurements and the temperature of formation of modern charcoals and implications for studies of fusain. *Bulletin de la Société géologique France* **162,** 193–200.

Kemp, E.M. (1981). Pre-Quaternary fire in Australia. In 'Fire and the Australian biota' (Eds A.M. Gill, R.A. Groves and I.R. Noble) pp 3–21. (Australian Academy of Science: Canberra)

Kenworthy, J.B. (1963). Temperatures in heather burning. *Nature (London)* **200,** 1226.

Kershaw, A.P. (1985). An extended late Quaternary vegetation record from north-eastern Queensland and its implications for the seasonal tropics of Australia. *Proceedings of the Ecological Society of Australia* **13,** 179–189.

Kershaw, A.P. (1986). Climatic changes and aboriginal burning in north-east Australia during the last two glacial/interglacial cycles. *Nature* **322,** 47–48.

Komarek, E.V., Sr. (1964). The natural history of lightning. *Proceedings of the Tall Timbers Fire Ecology Conference* **3,** 139–183.

Komarek, E.V., Sr. (1972). Ancient fires. *Proceedings of the Tall Timbers Fire Ecology Conference* **12,** 219–240.

Komarek, E.V., Sr. (1974). The effects of fire on temperate forests and related ecosystems, southeastern United States. In 'Fire and Ecosystems' (Eds T.T. Kozlowski. and C.E. Ahlgren) pp 251–277. (Academic press, New York)

Luke R.H., and McArthur, A.G. (1978). 'Bushfires in Australia'. (Australian Government Publishing Service: Canberra) 359 pp.

Macphail, M.K. and Truswell, E.M. (1989). Palynostratigraphy of the central west Murray Basin. *BMR Journal of Australian Geology and Geophysics* **11,**301–331

Martin, H.A (1984a). The stratigraphic palynology of the Murray Basin in New South Wales. II. The Murrumbidgee area. *Journal and Proceedings of the Royal Society of New South Wales* **117,** 35–44.

Martin, H.A (1984b). Stratigraphic palynology of the Murray Basin in New South Wales III. The Lachlan area. *Journal and Proceedings of the Royal Society of New South Wales* **117,** 45–51.

Martin, H.A. 1(987). The Cainozoic history of the vegetation and climate of the Lachlan River Region, New South Wales. *Proceedings of the Linnean Society of New South Wales* **109,** 214–257.

Martin, H.A (1991). Tertiary stratigraphic palynology and palaeoclimate of the inland river systems in New South Wales. In 'The Cainozoic of Australia: a re-appraisal of the evidence' (Eds M.A.J. Williams, P. De Dekker and A.P. Kershaw) *Special Publication of the Geological Society of Australia* **18,** 181–194

Martin, H.A. (1993). The palaeovegetation of the Murray Basin, late Eocene to mid Miocene *Australian Systematic Botany* **6,** 491–531.

Martin, H.A. (1994). Australian Tertiary phytogeography: evidence from palynology. In 'History of the Australian vegetation, Cretaceous to Recent' (Ed. R.S. Hill) pp. 104–142. (Cambridge University Press: Cambridge)

McGinnes, R.A., Kandeel, S.A. and Szopa, P.S.(1971). Some structural changes observed in the transformation of wood into charcoal. *Wood and Fibre* **3,** 77–83.

McGinnes, R.A., Szopa, P.S. and Phelps, J.E. (1974). Use of Scanning Electron Microscopy in studies of wood charcoal formation. In 'Scanning Electron Microscopy 1974 Part II' pp 469–476. (ITT Research Institute, Chicago, IL)

Nichols, G. and Jones, T. (1992). Fusain in Carboniferous shallow marine sediments, Donegal, Ireland: the sedimentological effects of wildfire. *Sedimentology* **39** 487–502.

Patterson, W.A., Edwards, K.J. and Macguire, D.J. (1987). Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews* **6,** 3–23

Prior, J. and Alvin, K.L. (1983). Structural changes on charring woods of *Dichrostachys* and *Salix* from Southern Africa. *IAWA Bulletin New Series* **4,** 197–206.

Rattigan, J.H. (1967). Phenomena about Burning Mountain, Wingen, New South Wales. *Australian Journal of Science* **30,** 183–84.

Sander, P.M. and Gee, C.T. 1(990). Fossil charcoal: techniques and applications. *Review of Palaeobotany and Palynology* **63,** 269–279.

Schopf, J. (1975). Modes of fossil preservation. *Review of Palaeobotany and Palynology* 20, 27–53.

Scott, A.C. (1989). Observations on the nature of fusain. *International Journal of Coal Geology* **12,** 443–475.

Singh, G., Kershaw, A.P. and Clark, R. (1981). Quaternary vegetation and fire history in Australia. In 'Fire and the Australian Biota' (Eds A.M. Gill, R.A. Groves and I.R. Noble) pp 23–54. (Australian Academy of Science: Canberra).

Teichmüller, M. (1982). Origin of petrographic constituents of coal. In 'Stach's Textbook of Coal Petrology' (Eds E. Stach, et al.) 3rd ed, English translation pp 219–294. (Gebrüder Borntraeger: Berlin).

Teichmüller, M. (1989). The genesis of coal from the viewpoint of coal petrology. *International Journal of Coal Geology* **12,** 1–87.

Webb, L.J. (1970). Eastern Australian environments in relation to fire. In 'Environments in order?' pp 5–8. Proceedings of a symposium, Australian Museum, 8th Aug. 1970 (unpubl.)

Whittaker, E. (1961). Temperatures in heath fires. *Journal of Ecology* **49,** 709–715.

Wolbach, W.S., Lewis, R.S., and Anders, E. (1985). Cretaceous extinctions: Evidence for wildfires and search for meteoritic material. *Science* **230,** 167–170.